Energy 44 (2012) 135–145

Contents lists available at SciVerse ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Total footprints-based multi-criteria optimisation of regional biomass energy supply chains

Lidija Čuček [a,*], Petar Sabev Varbanov [b], Jiří Jaromír Klemeš [b], Zdravko Kravanja [a]

[a] Faculty of Chemistry and Chemical Engineering, University of Maribor, Smetanova ulica 17, SI-2000 Maribor, Slovenia
[b] Centre for Process Integration and Intensification - CPI^2, Research Institute of Chemical and Process Engineering, Faculty of Information Technology, University of Pannonia, Egyetem u. 10, H-8200 Veszprém, Hungary

ARTICLE INFO

Article history:
Received 7 October 2011
Received in revised form
5 January 2012
Accepted 19 January 2012
Available online 4 March 2012

Keywords:
Biomass energy generation
Footprints
Total footprints
LCA
Multi-criteria optimisation
Regional energy supply chains

ABSTRACT

This paper presents a MCO (multi-criteria optimisation) of regional biomass supply chains for the conversion of biomass to energy through the simultaneous maximisation of economic performance and minimisation of the environmental and social FPs (footprints). The energy supply-chain model contains agricultural, pre-processing, processing, and distribution layers. An integrated model, previously developed by the authors, for regional biomass energy network optimisation is used as a basis, and now extended for simultaneous assessment of the supply-chain performance based on LCA (Life cycle assessment). Several total FPs are introduced for "cradle" to "grave" evaluation, which, besides direct, comprises also indirect effects caused by products' substitutions. In the MCO approach, the annual profit is maximised against each FP generating different sets of Pareto optimal solutions, one for each FP. With this approach the aggregation of different environmental and/or social pressures is thus avoided. The results indicate that total FPs enable the obtaining of more realistic solutions, than in those cases when only direct FPs are considered. More profitable and less environmentally harmful solutions can be gained with significant reduction in total carbon and total energy FPs.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

Currently a lot of research is being performed on the topics of alternative power/fuel generation [1–3]. Examples include fuel cells as a technology [4], the utilisation of solar energy [5], wind [6], geothermal [7], or tidal energy [8], as well as biomass energy applications (bioalcohols [9,10], biodiesel [11], and biohydrogen, biogas, bioheat and bioelectricity as well [12–17]). It is important that energy systems should be as sustainable as possible [18] and based on low carbon thermal processing.

When considering biomass utilisation, there are important issues for ensuring sustainable agriculture, as well as the optimisation of entire bioenergy supply chains [19]. Some of these important issues are obtaining energy by thermal conversion, water, and chemicals' usage, the economic situation, the world's growing population, climate change, and biodiversity. The distributed availability of biomass resources, their low density and high moisture content, could result in extensive requirements for transportation and pre-treatment, and therefore have a significant influence on logistics [16,20,21]. Another key issue to be considered in relation to exploiting biomass for energy generation is the competition with food production.

Several papers dealing with the optimisation and environmental assessment of biomass energy supply chains have been published. For example Zamboni et al. [22] developed a supply-chain optimisation model including environmental issues along with the economic one, illustrated by a case study of corn-based ethanol production system of northern Italy. Mele et al. [23,24] developed modelling framework for the design of supply chains for sugar and bioethanol production and illustrated it on a case study of co-production of sugar and bioethanol from sugar cane in Argentina. Gerber et al. [25] presented a methodology to integrate LCA (life cycle assessment) in thermo-economic models, illustrated by an application of combined synthetic natural gas and electricity production from lignocellulosic biomass.

However, by our knowledge until now no contribution appeared that describes general regional biomass and bioenergy supply-chain model and incorporates different environmental and/or social issues along with the economic one avoiding subjective aggregation of different environmental and/or social pressures, and besides that includes direct and indirect effects on the environment. The aim of this contribution was the development of the regional supply chains that include important environmental and

---

* Corresponding author. Tel.: + 386 222 94 455; fax: +386 225 27 774.
E-mail address: lidija.cucek@uni-mb.si (L. Čuček).

0360-5442/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2012.01.040

social FPs (footprints), based on direct and total FPs. For optimisation, the previously developed mathematical model [16] is used as a basis, and has been now upgraded for the simultaneous assessment of FPs. Previous work by authors [16] mainly considered CFP (carbon footprint) as an environmental performance indicator. CFP stands for a certain amount of gaseous emissions relevant to climate change, and is associated with human production and consumption activities [26]. Although the synonyms "climate footprint" [26] and "GHG (greenhouse gas) footprint" [27] are perhaps more appropriate, the term "CFP" is used in this paper, mainly due to its broader acceptance so far. "CFP" is usually defined based on the amount of CO_2 and other GHGs emitted over the full life cycle of a process or product, and expressed in mass unit per functional unit [28,29].

Besides GHG emissions, several other negative impacts may result from biomass production and use for bioenergy generation – water pollution and shortage, as well as food and land scarcity, to name a few.

Therefore, other environmental FPs should also be considered:

- Energy footprint – EFP. One of its definitions is that it represents the demand for non-renewable energy resources [30], expressed in energy unit per functional unit;
- Water footprint – WFP, defined as the total volume of direct and indirect freshwater used, consumed and/or polluted [31], expressed in volume unit per functional unit;
- Agricultural land footprint – LFP, the agricultural land area used for growing biomass for both food and energy [32], expressed in area unit per functional unit;
- Water pollution footprint – WPFP, the amount of substances emitted to water in the environment, expressed in mass unit per functional unit [33].

It should be noted, that environmental FPs are usually considered to be measured in units of area. However the data expressed in units of area show high variability and the high possible inaccuracy in results since they would have to be based on a variety of different assumptions (see e.g., Ref. [26]). Converting some of the FPs to an area units can prove to be problematic, especially for processes that are not primarily area-based such as chemical processes [34], therefore more appropriate unit for each of considered FP is used.

Food versus fuel competition for biomass utilisation is another very important issue relating to the usage of biomass for fuels (first generation biofuels), which should be considered. This problem is emphasised by the Nestlé chief executive: "*If, as predicted, we look to use biofuels to satisfy 20% of the growing demand for oil products, there will be nothing left to eat*" [35]. Another problem related to the biofuel industry is the global increase of food prices as a result of using more crops and land for energy purposes [36,37]. For this reason, a FEFP (food-to-energy footprint) should also be included as a special social FP in this study. It is defined as a mass-flow rate of food-intended crops converted into energy, expressed in mass unit per functional unit.

On the other hand, when considering the direct effects that different FPs have on the environment, this may result in misleading solutions. A much broader picture, leading to more complete estimates, can be obtained if the indirect effects caused by product substitution are considered, too. For instance, although the production of biofuels can cause a possibly significant direct burden on the environment, this effect is more than balanced out by the fact that biofuels substitute equivalent amounts of more harmful fossil-based fuels. Therefore, it is important that FPs account for both direct and indirect effects. The concept of total FPs is now introduced and applied to the biomass and bioenergy supply chain.

2. Implementation of sustainable criteria through total FPs

Biomass and bioenergy supply chains involve harvesting, storage, pre-treatment, conversion steps, distribution and usage of products, and transport amongst their activities. The superstructure of the considered supply chains is presented in Fig. 1.

It contains several layers dedicated to key activities:

(i) "Harvesting and supply" layer (layer 1 – L1) dedicated to raw material supplies
(ii) "Collection and pre-processing" layer (layer 2 – L2) for the pre-treatment of biomass when obtaining intermediates directly suitable for energy generation
(iii) "Main processing" layer (layer 3 – L3) comprising the core processes for energy and other bio-products' generation
(iv) "Use" layer (layer 4 – L4) comprising the usages of the energy products.

The transportation activities have no dedicated layer. Rather, they are embedded in the communication arrows between the layers.

The bioenergy supply-chain model, which consists of mass balances, production and conversion constraints, cost functions, profit objective function, and CFP calculation [16,17] has been extended to include the consideration of various environmental FPs. In addition to these, a FEFP is defined in order to evaluate the risk of diverting farmland for the production of fuel rather than food [38]. As a result, the mathematical model employs important direct, indirect, and total FPs (the sum of direct and indirect FPs)

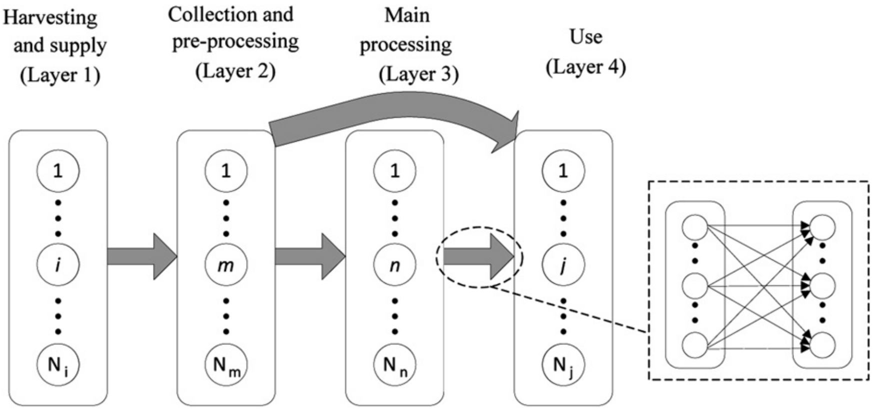
Harvesting and supply (Layer 1)
Collection and pre-processing (Layer 2)
Main processing (Layer 3)
Use (Layer 4)
1
i
N_i
1
m
N_m
1
n
N_n
1
j
N_j

Fig. 1. The superstructure of the biomass and bioenergy supply chains (after Ref. [16]).

along the whole supply chain. Different environmental FPs and FEFP are defined below, as per year and per unit of the supply-chain network's total area (A, km^2).

The model is formulated in the MI(N)LP (mixed-integer (non)-linear programming) form. The following sets have been defined within the model (Eqs. (1)–(9)):

i) Set I for supply zones within harvesting and supply layer (L1) with elements $i \in I$
ii) Set M for collection and pre-processing centres within collection and pre-processing layer (L2) with elements $m \in M$
iii) Set N for processing plants within main processing layer (L3) with elements $n \in N$
iv) Set J for demand locations within use layer (L4) (see Fig. 1) with elements $j \in J$
v) Set T for process technology options with elements $t \in T$
vi) Set P for products with elements $p \in P$
vii) Set PI for intermediate products $PI \subseteq P$ with elements $pi \in PI$
viii) Set PD for directly used products ($PD \subseteq P$) from the layer L2 with elements $pd \in PD$
ix) Set PP for products coming from the layer L3 ($PP \subseteq P$) with elements $pp \in PP$
x) Set PS for substituted products with elements $ps \in PS$
xi) Set F for environmental and social FPs with elements $f \in F$
xii) Set $PT = PI \times T$ for pairs of intermediate product, and the applicable process technology for it with elements $(pi,t) \in PT$
xiii) Set $PSP = PS \times PP$ for pairs of substituted product and produced product (if a produced product substitutes conventional product) with elements $(ps,pp) \in PSP$
xiv) Set $PIP = PI \times PP$ for pairs of intermediate products and produced products (if a produced product is produced from a given intermediate product) with elements $(pi,pp) \in PIP$

The definition of a direct environmental FP is:

- For the supply layer, $\text{ENVB}_f^{\text{L1}}$ is calculated from the production rate $q_{i,pi}^{m,\text{L1}}$ of biomass type $pi \in PI$ in supply zone $i \in I$, multiplied by the specific environmental FP $\text{ei}_{pi,f}^{\text{L1}}, f \in F$, caused by growing the biomass. The result is further summed over all the supply zones and biomass types, and divided by the supply network's total area (A):

$$\text{ENVB}_f^{\text{L1}} = \left(\sum_{i \in I} \sum_{pi \in PI \subseteq P} q_{i,pi}^{m,\text{L1}} \cdot \text{ei}_{pi,f}^{\text{L1}} \right) \Big/ A \quad \forall f \in F \tag{1}$$

- For the pre-treatment layer, $\text{ENVB}_f^{\text{L2}}$ – the mass-flow rate of biomass pi from the supply zone i in L1 to the pre-treatment centre $m \in M$ in L2, multiplied by the specific environmental FP for that biomass, $\text{ei}_{pi,f}^{\text{L2}}$, caused by pre-processing, and also evaluated per unit of total area (A) after the summation over all zones, pre-treatment centres, and biomass types:

$$\text{ENVB}_f^{\text{L2}} = \left(\sum_{i \in I} \sum_{m \in M} \sum_{pi \in PI \subseteq P} q_{i,m,pi}^{m,\text{L1,L2}} \cdot \text{ei}_{pi,f}^{\text{L2}} \right) \Big/ A \quad \forall f \in F \tag{2}$$

- For the processing layer, $\text{ENVB}_f^{\text{L3}}$ is obtained as the mass-flow rate of the intermediate product pi to the selected technology $t \in T$ at process plant $n \in N$ in L3, multiplied by the specific environmental FP for that product, $\text{ei}_{pi,t,f}^{\text{L3}}$, caused by processing and summed over all process plants, intermediate product types, technology options and pairs of intermediate products and the applicable process technology for it, divided by the network's total area (A):

$$\text{ENVB}_f^{\text{L3}} = \left(\sum_{n \in N} \sum_{pi \in PI \subseteq P} \sum_{t \in T} \sum_{(pi,t) \in PT} q_{n,pi,t}^{m,T,\text{L2,L3}} \cdot \text{ei}_{pi,t,f}^{\text{L3}} \right) \Big/ A \quad \forall f \in F \tag{3}$$

- For the use layer, $\text{ENVB}_f^{\text{L4}}$ is calculated as the mass-flow rate of the resources directly used from the collection and pre-processing layer (Fig. 1) $pd \in PD$ and also those products coming from the processing layer (plants) $pp \in PP$, each multiplied by the specific environmental FP for this product, $\text{ei}_{pd,f}^{\text{L4}}$ and $\text{ei}_{pp,f}^{\text{L4}}$, caused by their usage. The summation is performed over all pre-treatment centres (for direct products) or processing plants (for converted products), demand locations and product types per network's total area (A):

$$\text{ENVB}_f^{\text{L4}} = \left(\sum_{m \in M} \sum_{j \in J} \sum_{pd \in PD \subseteq P} q_{m,j,pd}^{m,\text{L2,L4}} \cdot ei_{pd,f}^{\text{L4}} + \sum_{n \in N} \sum_{j \in J} \sum_{pp \in PP \subseteq P} q_{n,j,pp}^{m,\text{L3,L4}} \cdot \text{ei}_{pp,f}^{\text{L4}} \right) \Big/ A \quad \forall f \in F \tag{4}$$

- Finally, for the transportation of materials between layers, the environmental FP $\text{ENVB}_f^{\text{tr}}$ is also defined per network's total area (A). Its value depends on the density of the biomass, distances ($D_{x,y}^{La,Lb}$), mode of transport, rate of biomass supply ($q_{x,y,p}^{m,\text{La,Lb}}$), and road conditions ($f_{x,y}^{\text{road},La,Lb}$). The specific environmental FP $\text{ei}_{p,f}^{\text{tr},La,Lb}$ is defined per t km:

$$\begin{aligned} \text{ENVB}_f^{tr} = \Bigg(& \sum_{i \in I} \sum_{m \in M} \sum_{pi \in PI \subseteq P} D_{i,m}^{\text{L1,L2}} \cdot f_{i,m}^{\text{road,L1,L2}} \cdot \text{ei}_{pi,f}^{\text{tr,L1,L2}} \cdot q_{i,m,pi}^{m,\text{L1,L2}} \\ & + \sum_{m \in M} \sum_{n \in N} \sum_{pi \in PI \subseteq P} D_{m,n}^{\text{L2,L3}} \cdot f_{m,n}^{\text{road,L2,L3}} \cdot \text{ei}_{pi,f}^{\text{tr,L2,L3}} \cdot q_{m,n,pi}^{m,\text{L2,L3}} \\ & + \sum_{m \in M} \sum_{j \in J} \sum_{pd \in PD \subseteq P} D_{m,j}^{\text{L2,L4}} \cdot f_{m,j}^{\text{road,L2,L4}} \cdot ei_{pd,f}^{\text{tr,L2,L4}} \cdot q_{m,j,pd}^{m,\text{L2,L4}} \\ & + \sum_{n \in N} \sum_{j \in J} \sum_{pp \in PP \subseteq P} D_{n,j}^{\text{L3,L4}} \cdot f_{n,j}^{\text{road,L3,L4}} \cdot \text{ei}_{pp,f}^{\text{tr,L3,L4}} \cdot q_{n,j,pp}^{m,\text{L3,L4}} \Bigg) \\ & \Big/ A \quad \forall f \in F \end{aligned} \tag{5}$$

Eq. (5) represents the environmental FP caused by transporting biomass *pi* from L1 to L2 (the first term), intermediate product *pi* from L2 to L3 (the second term), the directly used product *pd* from L2 to L4 (the third term), and the converted product in plant *pp* from L3 to L4 (the last term).

Note that specific environmental FPs are defined in t/MJ for heat, t/MWh for electricity, and t/t for other products.

- *The indirect environmental footprint* represents unburdening by product's substitution. When conventional energy is replaced by biomass energy, the indirect effect is a reduction of the FP. The indirect environmental FP for the use of biomass is then defined as the unburdening related to the substitution of conventional, mainly non-renewable products. The correlation between conventional energy and biomass energy is defined by the substitution factor $f^{\mathrm{sub}}_{ps,pp}$, where $ps \in PS$ is the substituted product, and $pp \in PP$ is the produced biomass product. With the generation of bioenergy and bioproducts, the supply and consumption of previously used resources is reduced in the amount specified by the substitution factors. The indirect environmental FP is defined as the product between the specific environmental FP for the substituted product, $\mathrm{ei}^{\mathrm{ind}}_{ps,f}$, the substitution factor for that product, $f^{\mathrm{sub}}_{ps,pp}$, and the mass-flow of the biomass product converted in the plant, $q^{m,\mathrm{L3,L4}}_{n,j,pp}$, per unit of total area. The summation is performed over all the substituted products, produced products and pairs of substituted products, and the produced products (if a produced product substitutes a conventional product) (first term), and over process plants, demand locations, and produced products (second term).

Note that the indirect environmental FP $\mathrm{ENVB}^{\mathrm{ind}}_{f}$ is negative, since the substitution causes unburdening:

$$\mathrm{ENVB}^{\mathrm{ind}}_{f} = -\left(\sum_{ps\in PS} \sum_{pp\in PP\subseteq P} \sum_{(ps,pp)\in PSP} \mathrm{ei}^{\mathrm{sub}}_{ps,f}\cdot f^{\mathrm{sub}}_{ps,pp}\cdot \sum_{n\in N}\sum_{j\in J}\sum_{pp\in PP\subseteq P} q^{m,\mathrm{L3,L4}}_{n,j,pp} \right) \Big/ A \quad \forall f\in F \tag{6}$$

- *The total environmental footprint* of the supply-chain's network is defined as a summation of all the direct FP elements, and the indirect FP correction:

$$\begin{aligned}\mathrm{ENVB}_f = {} & \mathrm{ENVB}^{\mathrm{L1}}_{f} + \mathrm{ENVB}^{\mathrm{L2}}_{f} + \mathrm{ENVB}^{\mathrm{L3}}_{f} + \mathrm{ENVB}^{\mathrm{L4}}_{f} \\ & + \mathrm{ENVB}^{\mathrm{tr}}_{f} + \mathrm{ENVB}^{\mathrm{ind}}_{f}\end{aligned} \tag{7}$$

- *The* FEFP is only defined for those multi-functional (multi-product) crops that can result in a supply of food, fodder, and energy. Biomass crops, which may take land that could be used for growing food crops, are not considered in this FP (FEFP is zero). This social FP is defined as a mass-flow rate of energy converted from food-intended crops. The FP is summed over all process plants, intermediate products going to plants, converted products from food crops in plants, technological options, and pairs of food-crop products and the applicable process technology for them (numerator), and over all the supply zones, pre-treatment centres and biomass types (denominator). Weight loss by drying and the conversion of intermediates into products is described using the conversion factor $f^{\mathrm{conv,L2}}_{pi}$. The FEFP is divided by the network's total area:

$$\mathrm{FEFP} = \left(\sum_{n\in N}\sum_{pi\in PI\subseteq P}\sum_{pp\in PP\subseteq P}\sum_{t\in T}\sum_{(pi,pp)\in PIP} q^{m,T,\mathrm{L2,L3}}_{n,pi,pp,t} \Big/ \left(f^{\mathrm{conv,L2}}_{pi}\cdot\left(\sum_{i\in I}\sum_{m\in M}\sum_{pi\in PI\subseteq P} q^{m,\mathrm{L1,L2}}_{i,m,pi}\cdot\left(1-w_{\mathrm{H_2O}}\right)\right)\right)\right) \Big/ A \tag{8}$$

2.1. The two-level multi-criteria approach

The synthesis is performed in two levels. At the first MI(N)LP level (MI(N)LP-1) the synthesis model from the previous work [16,17] plus different environmental FPs (ENVB_f) and FEFP (Eqs. (1)–(8)), is solved with the objective of maximising profit. Firstly, MI(N)LP-1 is used to obtain an initial or reference solution, representing the maximum profit possible/upper bound of the profit. This is then followed by solving MI(N)LP-2 for obtaining the multi-objective optimal solution(s).

MCO (Multi-criteria optimisation) is performed at the second MI(N)LP level (MI(N)LP-2). MCO, also known as multi-objective optimisation (MOO), is the process of simultaneously optimising two or more in many cases conflicting objectives, subject to certain constraints. Different methodologies can be applied for solving MOO problems. In this contribution the ε-constraint method [39] is applied and a sequence of constrained single-objective (MI(N)LP-2)$_i$ problems solved for each FP $f \in F$, as the maximisation of the profit P subjected to a relative FP (RFP_f). RFP is defined as the FP obtained at MI(N)LP-2 ($\mathrm{FP}(x,y)_f$) divided by the FP obtained at MI(N)LP-1 (FP^0_f). It decreases sequentially from the maximal FP obtained at MI(N)LP-1 ($\mathrm{RFP} = 1$) by a suitable step size $\Delta\varepsilon_{i,f}$ until there is no feasible solution.

The synthesis problem at MI(N)LP-2 takes the following form:

$$\begin{aligned} \max_{x,y}\ & P = c^T y + f(x) - \sum_{fr\neq f} 10^{-6}\cdot \mathrm{ENVB}_{fr} - \sum_{fr\neq f} 10^{-6}\cdot \mathrm{FEFP}_{fr} \\ \text{s.t.}\ & \mathrm{A}y + h(x,y) = 0 \\ & \mathrm{B}y + g(x,y) \le 0 \quad \left(\mathrm{MI(N)LP}_i\right)_f \\ & \mathrm{RFP}(x,y)_f \le \varepsilon_{i,f} \\ & \left(x^{\mathrm{LO}} \le x \le x^{\mathrm{UP}}\right) \in \boldsymbol{X} \subset \boldsymbol{R}^n, \quad y \in \boldsymbol{Y} = \{0,1\}^m \\ & \varepsilon_{i+1,f} = \varepsilon_{i,f} - \Delta\varepsilon_{i,f} \end{aligned}$$

where RFP is defined as

$$\mathrm{RFP}(x,y)_f = \frac{\mathrm{FP}(x,y)_f}{\mathrm{FP}^0_f} \tag{9}$$

x denotes the vector of continuous variables (flow-rates, design variables, etc.), y denotes the vector of binary variables (discrete decisions), and $f(x)$, $h(x,y)$ and $g(x,y)$ are the continuous non-linear constraint functions.

Note that MINLP_f is performed separately for each FP $f, f \in F$, while all the rest FPs $fr, fr \in F, fr \neq F$, are minimised with a small weight to provide solutions with the least values for those FPs in cases where multiple FP solutions exist. The weight should be very small in order not to interfere with the maximisation of profit, e.g., 10^{-6}.

At MI(N)LP-2 two sets of MCOs were performed: i) maximising the profit whilst simultaneously minimising the relative direct FPs and ii) maximising the profit whilst simultaneously minimising the relative total FPs (direct + indirect FPs). Different sets of Pareto optimal solutions, one for each FP, are generated at MI(N)LP-2 as 2-dimensional projections of a multi-dimensional problem, and so the subjective aggregation of different FPs, since they are usually expressed in different units, is thus avoided. Note that in case of negative FPs ε-inequality constraint is changed into an equality constraint and a single-parametric optimisation is performed. In this way, non-trade-off optimal solutions are obtained by the sequence of (MINLP-2)$_i$ where profit is maximised while relative FPs are incrementally increased from -1 to zero of even some positive values until there is no feasible solution at zero profit.

3. Demonstration case study

The above concept and developed model was applied within a regional biomass and bioenergy supply chain [16] (see Fig. 2). The region was divided into 10 zones (supply layers) with a total area of

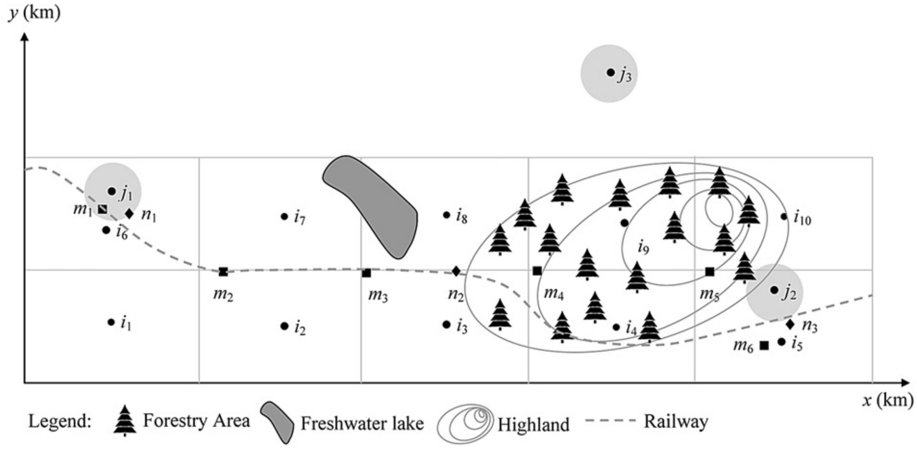

Fig. 2. A regional plan for the demonstrated regional biomass and bioenergy supply chain (after Ref. [16]).

1000 km^2. In the region there were six optional collection centres (m), three optional plants (n), two locations of local (j^o) and one of cross-regional demand (j^e). The geographical features of this network considered in the case study, are illustrated in Fig. 2.

Several biomass types, technology options and bioproducts were considered in the synthesis. The biomass types utilised were corn, corn stover, wood chips, MSW (municipal solid waste), manure, and timber. The technologies for converting biomass were the dry-grind process, anaerobic digestion, MSW incineration, timber sawing and incineration, and the produced bioproducts were bioelectricity, bioheat, bioethanol, boards, digestate, and DDGS (distiller's dried grains with solubles). Environmental impact was assessed through CFP. This case study [16] was now extended to employ different FPs originating from bioenergy, except CFP, which had already been evaluated in previous work [16,17].

The two newly-defined sets were: set F for FPs, $F=\{$CFP, EFP, WFP, LFP, WPFP, FEFP$\}$ and set PS for substituted products, $PS=\{$electricity mix, heat mix, gasoline, corn, inorganic fertiliser, steel$\}$.

The data for various specific FPs were taken from many different sources, and are given in Tables 1–3 for direct, and in Table 4 for indirect FPs. The rest of the data can be found in Čuček et al. [16].

3.1. Direct FPs

Direct FPs represent direct burden on the environment when biomass is used, pre-treated, processed and biomass products are utilised. Burdens are caused also by the transporting of raw materials to collection and pre-processing centres, to plants or directly to consumers, and by the transporting biomass products to consumers.

Table 1
Direct specific environmental footprints for biomass.

	Water (t/t)	Non-renewable energy consumption (GJ/t)	Emissions to water (t/t)	Emissions to air (t/t)
Corn grains	900 [40,41]	1.73 [43,44]	0.032 [46]	0.154 [43]
Corn stover[b]	900 [40,41]	1.73 [43,44]	0.032 [46]	0.154 [43]
Organic manure	0.75[a]	–	–	–
Wood chips[c]	2500 [42]	0.75 [45]	–	0.066 [47]
MSW	0.229[a]	–	–	–
Timber	1500 [42]	0.5 [45]	–	0.044 [47]

[a] Since organic manure and MSW are waste, there is no available data on WFP, and only raw materials moisture is taken as WFP.
[b] Assuming that from the entire plant mass around 50% is grain and 50% stover [9].
[c] Assuming the density of wood chips is approximately half density of timber [16].

The data for raw material's various direct specific environmental FPs *ei* are given in Table 1. Specific environmental FPs are defined in t (WFP, WPFP and CFP) and in GJ (EF) per t of biomass.

The data for various direct specific FPs caused by pre-treatment and processing per ton of intermediate product; for pre-treatment – biomass transported to collection and pre-processing centres, and for processing – pre-treated transported intermediate products, are given in Table 2.

In Table 3 direct specific environmental FPs for transport are presented. Biomass was transported by truck from the supply zone to pre-treatment centres (CC), with consumption of 0.3 L of petrol/km. Intermediate products were transported by rail from CCs to plants. Transport of direct products (corn intended for food) to consumers is assumed to be partly by truck, partly by rail, and produced products to consumers by truck. Bioethanol was transported to filling stations by tank trailers (cisterns). Electricity was transported by alternating current power lines; heat was used for buildings and water heating.

The environmental FPs for products are only assumed for digestate: CFP 0.017 t/t and WPFP 2.01 kg/t. The data in the literature vary significantly, environmental burdens are namely changed regarding the location, time, technology, composition etc., and, therefore, proper evaluation of LCA without measuring the FPs is impossible. Also, all other parameters vary considerably, such as

Table 2
Direct specific environmental footprints for pre-treatment and processing.

	Water (t/t)	Non-renewable energy consumption (GJ/t)	Emissions to water (t/t)	Emissions to air (t/t)
Dry-grind process	1.3 [48]	2.5 [53]	–	0.147 [16]
MSW incineration	0.31[b] [16]	–	0.0016 [55]	0.415 [16]
Anaerobic digestion	0.091 [50]	–	–	–
Sawing	10.6 [58]	0.036 [57]	–	0.00125 [49]
Corn stover compressing	0.005 [58]	0.01504 [51,59]	–	0.00262 [59]
Corn grain drying	0.5 [58]	1.251 [52,56]	–	0.09 [16]
Timber drying	0.004 [58]	0.0108[a] [54,60]	–	0.00078 [16]

[a] Air and kiln drying of wood is assumed where thermal energy for kiln drying is obtained from wood.
[b] A little higher water footprint than moisture content of MSW is assumed (22.9%, [16]).

Table 3
Direct specific environmental footprints for transport (in t/(t km) and in GJ/(t km)).

	Water (t/(t km)) [54]		Non-renewable energy consumption (GJ/(t km)) [45] [a]		Emissions to water (t/(t km))		Emissions to air (t/(t km)) [16]	
	Road	Rail	Road	Rail	Road	Rail	Road	Rail
Corn grains	1.36×10^{-4}	7.3×10^{-5}	3.89×10^{-4}	2.08×10^{-4}	–	–	5.3×10^{-5}	8×10^{-6}
Corn stover	2.33×10^{-3}	1.25×10^{-3}	6.67×10^{-3}	3.57×10^{-3}	–	–	1.1×10^{-3}	8×10^{-6}
Manure, digestate, DDGS	1×10^{-4}	–	2.8×10^{-4}	–	–	–	5.3×10^{-5}	–
Wood chips	4.9×10^{-4}	2.63×10^{-4}	1.4×10^{-3}	7.5×10^{-4}	–	–	2.4×10^{-4}	8×10^{-6}
MSW	5.6×10^{-4}	–	1.6×10^{-3}	–	–	–	1.3×10^{-4}	–
Bioethanol	1.24×10^{-4}	–	3.5×10^{-4}	–	–	–	2.7×10^{-5}	–
Boards, timber	2.45×10^{-4}	1.31×10^{-4}	7×10^{-4}	3.75×10^{-3}	–	–	5.3×10^{-5}	8×10^{-6}

[a] Rail: 0.15 MJ/(m^3·km), road: 0.28 MJ/(m^3·km).

biomass availability in the region, investment and operating cost, prices for raw materials and products, to name a few. It should be noted that this case study is just a demonstration case study which can be extended to any specific biomass energy supply chain. However, the quality of a solution depends on non-convexities involved in the model as when solving complex problems global optimality of solutions cannot be guaranteed.

3.2. Indirect FPs

Indirect FPs are set of FPs that indirectly unburden or benefit the environment when biomass products are utilised instead of conventional mainly fossil energy since its direct harmful impact on the environment is thus avoided. The correlation between conventional energy and biomass energy is defined by substitution factor $f^{sub}_{ps,pp}$. Substitution factors of substituted products to biomass products and their specific environmental FPs are presented in Table 4.

4. Results and discussion

Applying data from Tables 1–4 in the MI(N)LP supply-chain model [16,17], optimal solutions were obtained. At the MINLP-1 the optimal solution of 34 M€/y was obtained and FPs were calculated from the optimal solution.

The integrated MINLP model of regional biomass supply chain consisted of around 1100 continuous variables, 20 binary variables and 650 constraints and was solved in a fraction of a second. The MINLPs were performed using DICOPT/GAMS on a computer with 2.33 GHz Intel® Core™2 Quad Q8200 processor with 4.00 GB of RAM.

The calculated direct, indirect and total FPs at MINLP-1 are presented in Table 5.

Those values obtained were set as maximal FPs, and when normalised, set to 1.

From Table 5 it can be seen that by replacement of biomass energy and bioproducts for conventional energy and products, CFP and EFP are reduced, while on the other hand WFP and WPFP are increased. LFP and FEFP are zero for conventional fossil energy and therefore total LFP and FEFP remains the same as for direct FPs.

At MINLP-2 simultaneous maximisation of the profit and minimisation of the i) relative direct FPs and ii) relative total FPs were performed. By maximising the profit at MINLP-2, for each FP f out of six of them, a sequence of $(\text{MINLP}_i)_f$ was performed where a relative FP RFP_f was decreased from 1 (also increased from −1 for relative total FPs) to 0 (some positive value for relative total FPs) whilst the other FPs ff, were calculated. Thus a set of Pareto curves was obtained, one for each FP [71].

4.1. Direct FPs

In this paper only the main Pareto curves are presented where a normalised FP f was decreased from 1 to 0 by suitable step size. In Fig. 3 profit versus relative direct FPs are presented. Note that FPs are normalised so that each FP is divided by its maximal value obtained at MINLP-1 (Eq. (9)).

It can be seen that the FEFP especially differed from FPs. The lower profit was obtained by lower FEFPs, and that means that it is economically more preferable to produce energy rather than food. All other FPs showed similar behaviour with slight concave curvatures caused by the fact that for increasing the profit less and less sustainable alternatives should be selected. The profit increased at the lowest RFPs most steeper, for approximately 4.7 M€/y per 0.1 of RFP, while at the RFP 0.3 and higher only for approximately 2.9 M€/y per 0.1 of RFP.

Heat and electricity were generated by all ranges of different FPs; bioethanol and DDGS as well were produced by all ranges of RFPs except by lower CFPs (below 0.25) and EFPs (below 0.65), anaerobic digestion was selected within the whole range of EFPs, LFPs, WFPs, and FEFPs, and in the lower range of CFPs and WPFPs. Board-making was selected by the whole range of LFPs, WPFPs, and FEFPs, and food was not produced by the whole range of WFPs, WPFPs and LFPs. In Fig. 4 profit versus relative products flow-rates are presented when relative direct CFP was simultaneously minimised with maximising the profit. The maximal flow-rates of products when their relative flow-rates are 1, are: 243 GWh/y of electricity, 1.25 PJ/y of heat, 62.2 kt/y of ethanol,

Table 4
Substitution factors and specific environmental footprints of substituted products.

	Substitution factor	Water	Non-renewable energy consumption	Emissions to water (t/t)	Emissions to air
Electricity mix/electricity	1/1	1.26 t/MWh [58] [a]	3.6 GJ/MWh	–	0.15 t/MWh [63]
Heat mix/heat	1/1	0.175 t/GJ [58] [a]	1 GJ/GJ	–	0.076 t/GJ [63]
Gasoline/bioethanol	1/1.53	3 t/t [67]	44.4 GJ/t	0.12 [68,69]	3.9 t/t [63]
Corn/DDGS	1/1.2 [70]	900 t/t [66]	15.9 GJ/t [16]	0.032 [46]	0.154 t/t [43]
Inorganic fertilizer/digestate	1/34 [61,62]	150 t/t [65]	40 GJ/t [44]	1.15 [68,69] [b]	2.508 t/t [63]
Steel/Boards	1/1	260 t/t [65]	35 GJ/t [64]	0.02 [68,69]	1.609 t/t [63]

[a] The average WFP of a mix of uranium, natural gas, coal and crude oil is 0.35 m^3/GJ.

[b] The values for the amounts of used fertilisers are taken from Ref. [68] for corn, production in the USA.

Table 5
Direct, indirect and total footprints obtained at MINLP-1.

	Direct footprints	Indirect footprints	Total footprints
CFP (t/(km^2 y))	117.65	−311.95	−194.3
WFP (t/(km^2 y))	376,500.75	−39,210.75	337,290
EFP (GJ/(km^2 y))	1440.65	−4906.72	−3466.07
WPFP (t/(km^2 y))	12.02	−6.47	5.55
LFP (km^2/(km^2 y))	0.32	0	0.32
FEFP (−)	0.38	0	0.38

3.65 kt/y of organic fertiliser, 48.1 kt/y of ethanol, 9.5 kt/y of boards and 192 kt/y of corn.

4.2. Total FPs

Total FPs are composed of direct and indirect FPs. The values at MINLP-1 (last column in Table 5) were used to normalise FPs obtained at MINLP-2. Total FPs were divided by their absolute value of FP at MINLP-1 and therefore relative total FPs were presented on the *x*-coordinate from +1 to 0 (positive total FPs) and from −1 to 0 or even higher value (negative total FPs). In Fig. 5 Pareto curves for profit versus relative total FPs are presented. In case of initially negative FPs the curves are obtained by the sequence of $(\text{MINLP-2})_i$ where profit is maximised while relative total FPs are incrementally increased from −1 to some positive values until there is no feasible solution at zero profit. In those cases the MCO changed to single-parametric $(\text{MINLP-2})_i$, where relative FPs RFP_f are equal to ε, and sets of non-trade-off optimal solutions are thus obtained, since relative FPs lowered despite that profit increased. In case of initially positive FPs the profit is maximised while their relative total FP is decreased incrementally from +1 to 0.

From the above Fig. 5 it can be seen that total CFPs and EFPs showed similar behaviour (mainly negative), from which it can be gathered that they are in relation. Similar behaviour also showed WFPs, WPFPs and LFPs and are always positive. The reasons are: biomass energy requires more water, large land areas and some biomass also requires large amounts of chemicals which cause pollution to water. All this is not the case for conventional energy (mainly fossil). From Fig. 5 it can be seen that with biomass energy CFPs and EFPs are reduced compared to currently used energy, while on the other hand WFPs, WPFPs, LFPs and FEFPs are increased. It also should be noted that by zero total CFP much higher profit (14.4 M€/y) is obtained compared to direct alternative.

The production of biomass products versus total FPs shows similar trends as versus direct FPs. In Fig. 6 relative products flow-rates versus profit are presented when total relative CFP was simultaneously stepwise increased to zero profit with maximising the profit. The maximal flow-rates of products are the same as by direct FPs. Heat and electricity were again generated by all ranges of different FPs, however their production was higher compared to the direct alternative, by the zero CFP 145 GWh/y of electricity and 0.75 PJ/y of heat were generated (1.2 kWh/y of electricity and 6.03 MJ/y of heat for direct alternative), and by the zero profit 35.3 GWh/y of electricity and 0.18 PJ/y of heat were generated. Bioethanol, DDGS and boards showed similar trends for relative direct and total CFPs. Corn production was increased with increasing CFP, by the zero profit maximal amount of corn was produced, and digestate was only produced by the lowest CFP.

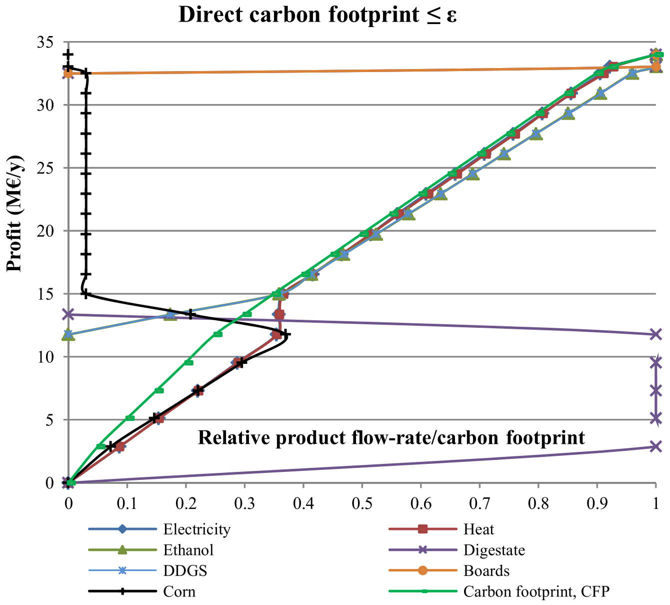

Fig. 4. Profit versus relative products flow-rates for the case where direct CFP was minimised.

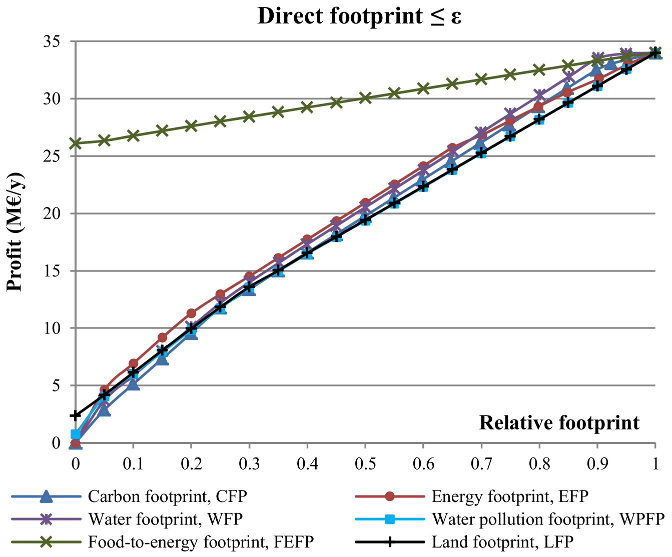

Fig. 3. Profit versus direct specific relative footprints.

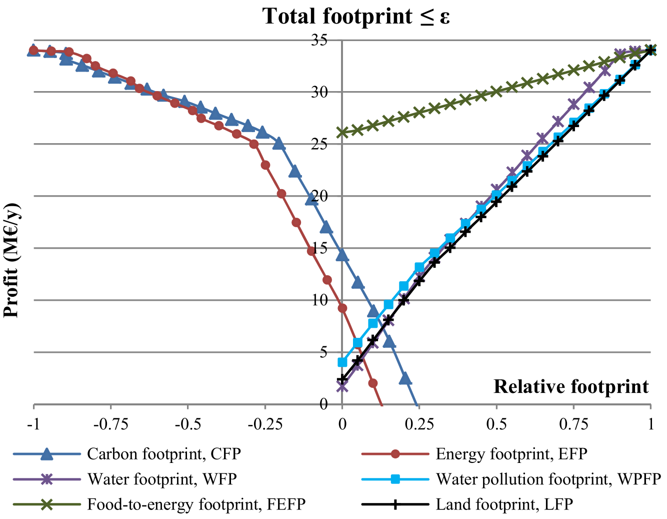

Fig. 5. Profit versus total footprints.

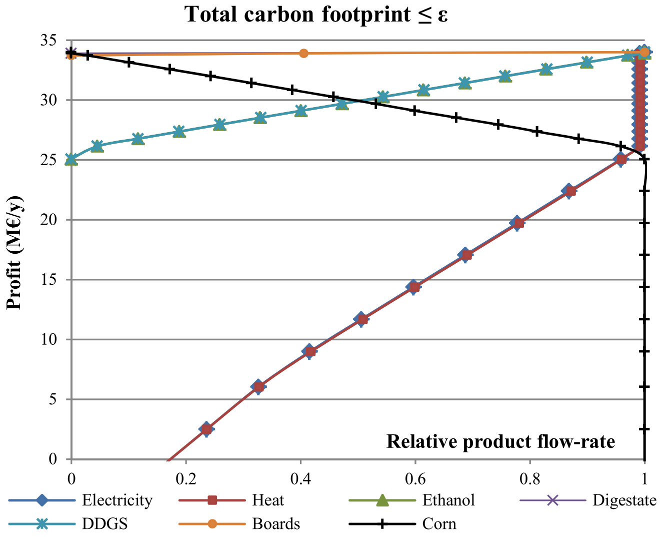

Fig. 6. Profit versus relative products flow-rates for the case where total CFP was stepwise increased to zero.

4.3. Total/direct FPs

If relative FPs for total FPs are defined as total FPs divided by values of the corresponding direct FPs obtained at MINLP-1 (relative total/direct FPs), then we get some additional information about how much better (or worse) are total FPs than direct FPs because of product's substitution effects. If a relative total/direct FP evaluated at maximal value of profit gets a value less than 1 means that a total FP has a lower value than its corresponding direct FP and consequently, product's substitution helps decreasing environmental burdening, especially when it gets very negative values. Fig. 7 shows Pareto curves for profit versus relative total/direct FP for the case study. All relative total/direct FPs but for LFP and FEFP are decreased compared to their direct impacts, especially EFP and CFP which are very negative and substantially unburden the environment compared to currently used energy. Positive but less than 1 are relative total/direct FPs for WPFP and WFP meaning that their burdens are decreased compared to their direct impacts but not diminished. Only relative total FPs for LFP and FEFP are the same as their direct impacts, because production of biomass requires large land areas and production of energy from food-intended crops consumes large amounts of these crops. Note that absolute values of total FPs at maximal profit are written at the ends of their Pareto curves. Note also that these total FP curves in Fig. 7 can be now directly compared to direct FP ones in Fig. 3 since all of them are normalised using the same FP values.

5. Conclusions

This contribution presented MCO of the regional biomass and bioenergy supply chains in order to maximise the economic performance of the supply chain by simultaneously minimising different environmental FPs and special FEFP. Direct, indirect (compared to the current situation) and also total (direct + indirect) environmental FPs were studied in this multi-criteria approach. The problem was solved in two steps, at MINLP-1 profit was maximised and 'maximal' ('minimal' total CFPs and EFPs) FPs were calculated, and then at MINLP-2 MOO was performed, where simultaneously profit was maximised and each RFP was stepwise minimised (stepwise increased from −1 for CFPs and EFPs). Different trade-offs were obtained between the network's alternatives.

From the optimisation of the total FPs it was seen that CFP and EFP are reduced while WFP, WPFP and LFP are increased compared to conventional mainly fossil energy. Biomass energy compared to conventional energy requires much more water, transport, chemicals, cause pollution to water, and it requires also large land areas. It is interesting to note that CFP and EFP on the one hand, and WFP, WPFP and LFP on the other hand showed similar common behaviour. It is clear that product substitution can have significant effect on

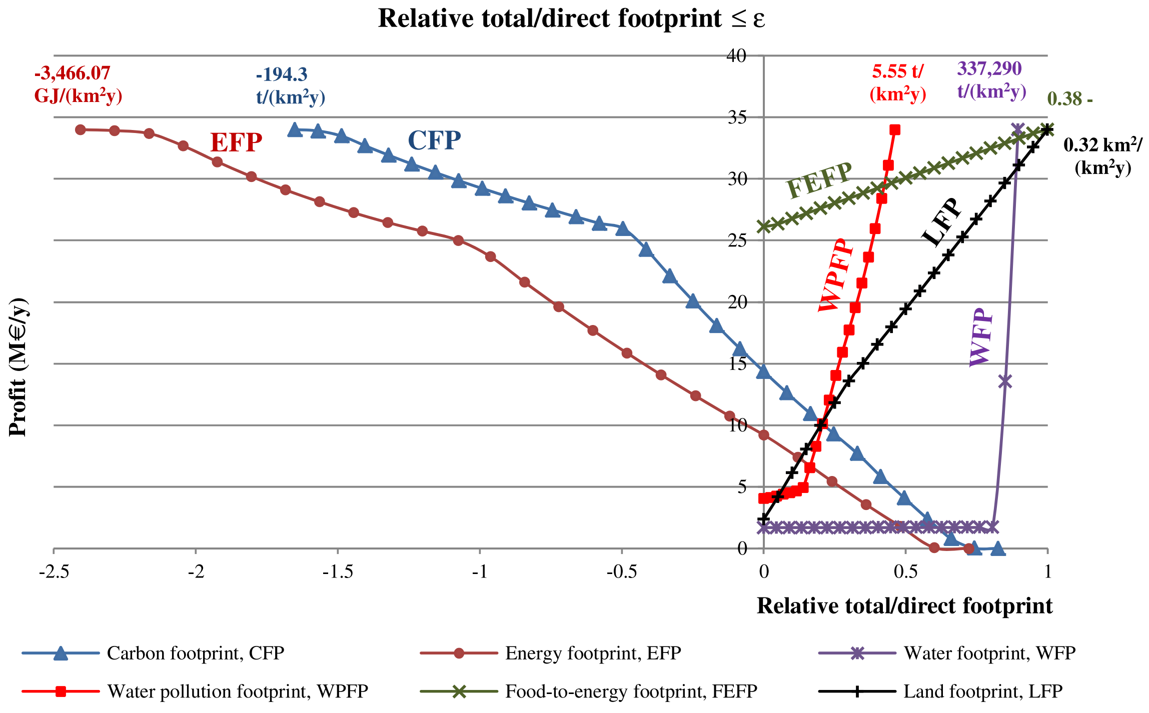

Fig. 7. Profit versus relative total/direct footprint.

total FPs and should be considered. According to the solution obtained by minimising relative total/direct FPs, total EFP is reduced by about factor -2.4, total CFP by -1.4, and even relative total WPFP and WFP to $+0.5$ and $+0.8$, when compared to their direct values.

In the future the number of environmental FPs should be reduced to a minimum of "independent" FPs through correlations among FPs. In the set only one FP, an "independent" one, can be considered within the MOO whilst the rest of the "dependent" FPs can be evaluated after optimisation from the independent ones. In this way, the dimensionality of the criteria within the MOO can be significantly reduced, so that a multi-parametric optimisation can be performed with independent FPs as parameters, thus avoiding the subjective weighting of environmental pressures. The correlations from other FPs should also be investigated, as assessed in this contribution, such as nitrogen and phosphorus FPs, and the issue of biodiversity measured by biodiversity FP.

Acknowledgement

The authors are grateful for the financial support from the Slovenian Research Agency (Program No. P2-0032 and PhD research fellowship contract No. 1000-08-310074).

Nomenclature

Superscripts

L1	harvesting and supply layer
L2	collection and pre-processing layer
L3	main processing layer
L4	use layer
ind	indirect
road	road conditions
sub	substituted product
tr	transport

Sets

F	set of footprints
I	set of supply zones
J	set of demand locations
M	set of collection and intermediate process centres
N	set of process plants
P	set of products
PS	set of substituted products
T	set of technology options

Subsets

PD	set of directly used products (subset of P)
PI	Set of intermediate products (subset of P)
$PIP = PI \times PP$	set of pairs of intermediate product and produced product (if a produced product is produced from a given intermediate product)
PP	set of produced products from plants (subset of P)
$PSP = PS \times PP$	set of pairs of substituted product and produced product (if a produced product substitutes conventional product)
$PT = PI \times T$	set of pairs of intermediate product and applicable process technology for it

Indexes

f	index for footprints
i	index for supply zones
j	index for demand locations
m	index for collection and intermediate process centres
n	index for process plants
p	index for products
pd	index for directly used products
pi	index of intermediate products
pp	index for directly used products
ps	index for substituted products
t	index for technology options

Scalars

A	supply-chain network's total area, km^2
$w_{\mathrm{H_2O}}$	mass fraction of water

Parameters

$\mathrm{ei}^{\mathrm{L}a}_{pi,f}$	specific environmental footprint f of intermediate product pi at layer a, $a = \{1,2\}$, t/t or GJ/t or km^2/t
$\mathrm{ei}^{\mathrm{L3}}_{pi,t,f}$	specific environmental footprint f of intermediate product pi and the selected technology t at processing layer, t/t or GJ/t or km^2/t
$\mathrm{ei}^{\mathrm{L4}}_{p,f}$	specific environmental footprint f of product p at use layer, t/t
$\mathrm{ei}^{\mathrm{sub}}_{ps,f}$	specific environmental footprint f of substituted product ps, (t or GJ)/(MWh or GJ or t)
$f^{\mathrm{conv,L2}}_{pi}$	conversion factor of intermediate product pi by pre-processing
$f^{\mathrm{sub}}_{ps,pp}$	substitution factor between use of conventional energy ps and biomass energy pp

Continuous variables

$\mathrm{ENVB}^{\mathrm{L}a}_{f}$	direct environmental footprint f at layer a, t/(km^2 y) or GJ/(km^2 y) or km^2/(km^2 y)
$q^{m,\mathrm{L1}}_{i,pi}$	production rate of intermediate product pi at supply zone i, t/y
$q^{m,T,\mathrm{L2,L3}}_{n,pi,t}$	mass-flow of intermediate product pi to the selected technology t at the process plant n, t/y
$q^{m,\mathrm{L}a,\mathrm{L}b}_{x,y,p}$	mass-flow of product p from object x in layer a to object y in layer b, t/y
$D^{\mathrm{L}a,\mathrm{L}b}_{x,y}$	distance between object x in layer a and object y in layer b, km
$f^{\mathrm{road,L}a,\mathrm{L}b}_{x,y}$	road condition factor between object x in layer a and object y in layer b
$ei^{\mathrm{tr,L}a,\mathrm{L}b}_{p,f}$	transport environmental footprint f from layer a to the layer b, t/(t km) or GJ/(t km)
$q^{m,T,\mathrm{L2,L3}}_{n,pi,pp,t}$	mass-flow of produced products pp from intermediate product pi with the selected technology t at the process plant n, t/y
$\mathrm{ENVB}^{\mathrm{ind}}_{f}$	indirect environmental footprint type f, t/(km^2 y) or GJ/(km^2 y)
ENVB_{f}	total environmental footprint type f, t/(km^2 y) or GJ/(km^2 y) or km^2/(km^2 y)

Abbreviations

CC	Collection and pre-treatment centre
CFP	Carbon footprint
DDGS	Distiller's dried grains with solubles
EFP	Energy footprint
FEFP	Food-to-energy footprint
FP	Footprint
GHG	Greenhouse gas
LCA	Life cycle assessment, also Life cycle analysis
LFP	Agricultural land footprint
MCO	Multi-criteria optimisation
MINLP	Mixed-integer non-linear programming
MOO	Multi-objective optimisation
MSW	Municipal solid waste
RFP	Relative footprint
WFP	Water footprint
WPFP	Water pollution footprint

References

[1] Shen YS, Chou CJ, Lin GTR. The portfolio of renewable energy sources for achieving the three E policy goals. Energy 2011;36:2589–98.
[2] Duić N, Guzovič Z, Lund H. Sustainable development of energy, water and environment systems. Energy 2011;36:1839–41. Editorial.
[3] Rout UK, Voß A, Singh A, Fahl U, Blesl M, Gallachóir BPO. Energy and emissions forecast of China over a long-time horizon. Energy 2011;36:1–11. Review.
[4] Varbanov P, Klemeš J. Analysis and integration of fuel cell combined cycles for development of low-carbon energy technologies. Energy 2008;33(10):1508–17.
[5] Kelly NA, Gibson TL. Increasing the solar photovoltaic energy capture on sunny and cloudy days. Solar Energy 2011;85(1):111–25.
[6] Redha AM, Dincer I, Gadalla M. Thermodynamic performance assessment of wind energy systems: an application. Energy 2011;36:4002–10.
[7] Guzovič Z, Lončar D, Ferdelji N. Possibilities of electricity generation in the Republic of Croatia by means of geothermal energy. Energy 2010;35:3429–40.
[8] Li Y, Lence BJ, Calisal SM. An integrated model for estimating energy cost of a tidal current turbine farm. Energy Conversion and Management 2011;52:1677–87.
[9] Čuček L, Martín M, Grossmann IE, Kravanja Z. Energy, water and process technologies integration for the simultaneous production of ethanol and food from the entire corn plant. Computers and Chemical Engineering 2011;35(8):1547–57.
[10] García V, Päkkilä J, Ojamo H, Muurinen E, Keiski RL. Challenges in biobutanol production: how to improve the efficiency. Renewable and Sustainable Energy Reviews 2011;15(2):964–80.
[11] Tan KT, Lee KT, Mohamed AR. Potential of waste palm cooking oil for catalyst-free biodiesel production. Energy 2011;36:2085–8.
[12] Martín M, Grossmann IE. Energy optimization of hydrogen production from lignocellulosic biomass. Computers and Chemical Engineering 2011;35:1798–806.
[13] Drobež R, Novak Pintarič Z, Pahor B, Kravanja Z. Simultaneous heat integration and the synthesis of biogas processes from animal waste. Asia-Pacific Journal of Chemical Engineering 2011;6(5):734–49.
[14] Touš M, Pavlas M, Stehlík P, Popela P. Effective biomass integration into existing combustion plant. Energy 2011;36:4654–62.
[15] Münster M, Meibom P. Optimization of use of waste in the future energy system. Energy 2011;36:1612–22.
[16] Čuček L, Lam HL, Klemeš JJ, Varbanov PS, Kravanja Z. Synthesis of regional networks for the supply of energy and bioproducts. Clean Technologies and Environmental Policy 2010;12:635–45.
[17] Lam HL, Klemeš JJ, Kravanja Z. Model-size reduction techniques for large-scale biomass production and supply networks. Energy 2011;36(8):4599–608.
[18] Gwehenberger G, Narodoslawsky M. Sustainable processes—the challenge of the 21st century for chemical engineering. Process Safety and Environment Protection 2008;86:321–7.
[19] Papapostolou C, Kondili E, Kaldellis JK. Development and implementation of an optimisation model for biofuels supply chain. Energy 2011;36:6019–26.
[20] Uslu A, Faaij APC, Bergman PCA. Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. Energy 2008;33:1206–23.
[21] Ren H, Zhou W, Nakagami K, Gao W. Integrated design and evaluation of biomass energy system taking into consideration demand side characteristics. Energy 2010;35:2210–22.
[22] Zamboni A, Bezzo F, Shah N. Spatially explicit static model for the strategic design of future bioethanol production systems. 2. Multi-objective environmental optimization. Energy Fuels 2009;23:5134–43.
[23] Mele FD, Guillén-Gosálbez G, Jiménez L. Optimal planning of supply chains for bioethanol and sugar production with economic and environmental concerns. Computer Aided Chemical Engineering 2009;26:997–1002.
[24] Mele FD, Kostin AM, Guillén-Gosálbez G, Jiménez L. Multiobjective model for more sustainable fuel supply chains. A case study of the sugar cane industry in Argentina. Industrial & Engineering Chemistry Research 2011;50:4939–58.
[25] Gerber L, Gassner M, Maréchal F. Systematic integration of LCA in process systems design: application to combined fuel and electricity production from lignocellulosic biomass. Computers and Chemical Engineering 2011;35:1265–80.
[26] Wiedmann T, Minx J. A definition of 'carbon footprint'. In: Pertsova CC, editor. Ecological economics research trends: Ch 1. Hauppauge, NY, USA: Nova Science Publisher; 2008. p. 1–11.
[27] Berners-Lee M, Howard DC, Moss J, Kaivanto K, Scott WA. Greenhouse gas footprinting for small businesses – the use of input-output data. Science of the Total Environment 2011;409:883–91.
[28] UK Parliamentary Office of Science and Technology, POST. Carbon footprint of electricity generation; 2006. London, UK, No 268.
[29] Perry S, Klemeš JJ, Bulatov I. Integrating waste and renewable energy to reduce the carbon footprint of locally integrated energy sectors. Energy 2008;33:1489–97.
[30] Schindler, Energy & GHG footprint, A big step forward, <ccr.schindler.com> [accessed 19.02.11].
[31] Hoekstra AY. In: Virtual water trade. Proceedings of the international expert meeting on virtual water trade. The Netherlands: IHE Delft; 2003.
[32] Kissinger M, Gottlieb D. Place oriented ecological footprint analysis – the case of Israel's grain supply. Ecological Economics 2010;69:1639–45.
[33] Sánchez-Chóliz J, Duarte R. Water pollution in the Spanish economy: analysis of sensitivity to production and environmental constraints. Ecological Economics 2005;53:325–38.
[34] De Benedetto L, Klemeš JJ. The environmental performance strategy map: an integrated LCA approach to support the strategic decision-making process. Journal of Cleaner Production 2009;17(10):900–6.
[35] Asch F, Heuelsebusch C. Agricultural research for development in the tropics: caught between energy demands and food needs. Journal of Agriculture and Rural Development in the Tropics and Subtropics 2009;110:75–91.
[36] Index Mundi, <www.indexmundi.com> [accessed 07.07.11].
[37] Peters G. A look behind rising food prices: population growth; rising oil prices; weather events, <oilprice.com>; 2011 [accessed 07.07.11].
[38] Čuček L, Kravanja Z. Sustainable LCA-based MI(N)LP synthesis of bioethanol processes. Computer Aided Chemical Engineering 2010;28:1889–94.
[39] Haimes Y, Lasdon L, Wismer D. On a bicriterion formulation of the problems of integrated system identification and system optimization. IEEE Transactions on Systems, Man, and Cybernetics 1971;1:296–7.
[40] Hoekstra A.Y., The water footprint of food, water for food, pp. 49–61, <www.waterfootprint.org> [accessed 20.06.11].
[41] Hoekstra AY, Chapagain AK. Water footprints of nations: water use by people as a function of their consumption patterns. Water Resources Management 2007;21:35–48.
[42] Van Oel PR, Hoekstra AY. The green and blue water footprint of paper products: methodological considerations and quantifications. Value of Water Research Report Series No. 46. The Netherlands: UNESCO-IHE, Delft; 2010.
[43] Kim S, Dale BE. Life cycle assessment of various cropping systems utilized for producing biofuels: bioethanol and biodiesel. Biomass and Bioenergy 2005;29:426–39.
[44] Patzek TW. Thermodynamics of the corn-ethanol biofuel cycle. Critical Reviews in Plant Sciences 2004;23(6):519–67.
[45] Puettmann ME, Wilson JB. Life cycle analysis of wood products: cradle-to-gate LCI of residential wood building materials. Wood and Fiber Science 2005;37:18–29. CORRIM Special Issue.
[46] Nielsen PH, Wenzel H. Environmental assessment of ethanol produced from corn starch and used as an alternative to conventional gasoline for car driving, the Institute for Product Development. Lyngby, Denmark: Technical University of Denmark, <www.ipu.dk>; 2005 [accessed 05.07.11].
[47] Ply Machine, <plymachine.com/complete_Particle_Board_production_line.aspx> [accessed 18.02.11].
[48] Martín M. Synthesis and optimization of biofuel production processes, <egon.cheme.cmu.edu/esi>; 2011 [accessed 04.07.11].
[49] The UNEP SETAC Life Cycle Initiative. Life cycle assessment. A product-oriented method for sustainability analysis. Training manual, <lcinitiative.unep.fr>; 2008 [accessed 05.07.11].
[50] Drobež R, Novak Pintarič Z, Pahor B, Kravanja Z. MI(N)LP synthesis of heat integrated processes for the production of biogas from poultry and other organic waste. In: 7th European congress of chemical engineering, ECCE-7, conference proceedings, paper 1027; 2010.
[51] Mani S, Tabil LG, Sokhansanj S. Specific energy requirement for compacting corn stover. Bioresource Technology 2006;97:1420–6.
[52] Maier DE, Bakker-Arkema FW. Grain drying systems; 2002. Illinois, USA.
[53] Karuppiah R, Peschel A, Grossmann IE, Martín M, Martinson W, Zullo L. Energy optimization for the design of corn based ethanol plants. AIChE Journal 2008;54:1499–525.
[54] Helin M. Moisture of wood fuels and drying of wood chips, <www.northernwoodheat.net>; 2005 [accessed 06.07.11].
[55] European Commission. Integrated pollution prevention and control, reference document on the best available techniques for waste incineration, <ftp.jrc.es/eippcb/doc/wi_bref_0806.pdf>; 2006 [accessed 08.07.11].
[56] Liviu G, Badea L. Aspects into the use of renewable energy sources in cereal drying process. In: Proceedings of the 8th WSEAS international conference on signal processing, robotics and automation; 2009. pp. 74–7.
[57] McCurdy MC, Li J, Pang S. Modelling of energy demand in a sawmill, Auckland, New Zealand. In: Conference proceedings of CHEMECA 2006: knowledge and innovation, <ir.canterbury.ac.nz>; 2006 [accessed 06.07.11].
[58] Gerbens-Leenes W, Hoekstra A, van der Meer T. The water footprint of energy consumption: an assessment of water requirements of primary energy carriers. ISESCO Science and Technology Vision 2008;4(5):38–42.
[59] Morey RV, Kaliyan N, Tiffany DG, Schmidt DR. A biomass supply logistics system. In: An ASABE meeting presentation, Paper No. 096660; 2009.
[60] Puettmann ME, Wagner FG, Johnson L. Life cycle inventory of softwood lumber from the inland northwest US. Wood and Fiber Science 2010;42:52–66. CORRIM Special Issue.
[61] European Commission, Directorate-General for Energy and Transport, Demonstration of an optimized system for biogas from biological waste and agricultural feedstock, Svensk växtkraft AB, Sweden, <www.managenergy.net/download/nr304.pdf> [accessed 04.07.11].
[62] Čuček L, Drobež R, Pahor B, Kravanja Z. Sustainable LCA-based MIP synthesis of biogas processes. Computer Aided Chemical Engineering 2011;29:1999–2003.
[63] Delft University of Technology, the Netherlands, <www.ecocostvalue.com> [accessed 04.07.11].
[64] Shukla PR, Rana A, Garg A, Kapshes M, Nair R. Climate policy assessment for India: applications of Asia-Pacific integrated model (AIM). Hyderabad, India: University Press; 2004.

[65] Gleick PH, Cooley H, Cohen MJ, Morikawa M, Morrison J, Palaniappan M. The world's water 2008–2009 the biennial report on freshwater resources. Washington, US: Island Press; 2009.
[66] Water Footprint, <www.waterfootprint.org> [accessed 04.07.11].
[67] Jordan J. What's your water footprint, tx H_2O. Texas Water Resources Institute 2009;5(2):21–3.
[68] Ecoinvent Database, Ecoinvent Centre, Swiss Centre for Life Cycle Inventories, <www.ecoinvent.org> [accessed 04.07.11].
[69] PE, LBP: GaBi 4 software-system and databases for life cycle engineering. Copyright, TM, Stuttgart, Echterdingen, <www.gabi-software.com>; 1992–2008 [accessed 04.07.11].
[70] Wisner R. Evolution of the market. Ethanol Producer Magazine, <www.ethanolproducer.com>; 2011 [accessed 04.07.11].
[71] Čuček L, Klemeš JJ, Varbanov PS, Kravanja Z. Life cycle assessment and multi-criteria optimization of regional biomass and bioenergy supply chains. Chemical Engineering Transactions 2011;25:575–80.